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RAIN EROSION RESISTANCE OF MATERIALS FOR FORWARD LOOKING INFRAR--ETC(U)
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RAIN EROSION RESISTANCE OF MATERIALS FOR FORWARD LOOKING INFRARED WINDOWS

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PREPARED BY:

DIRECTORATE OF AVIONICS ENGINEERING
AERONAUTICAL SYSTEMS DIVISION
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This engineering report has been reviewed and is approved for release as written.

LOUIS J. URBAN
Technical Director
Directorate of Avionics Engineering

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RAIN EROSION RESISTANCE OF MATERIALS

FOR FORWARD LOOKING INFRARED WINDOWS

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FOREWORD

This report summarizes the theory and data which has been compiled to date on the rain erosion resistance of Zinc Sulfide, Zinc Selenide and Gallium Arsenide. In addition, it formulates a method by which the usefulness of these and other IR materials in operational systems can be predicted. —> [illegible]

This information should prove useful to managers and engineers participating in the development of airborne systems requiring an infrared window. Due to the vast number of possible combinations of conditions, configurations and material properties, it is probable that a simple answer to the question of rain erosion resistance for a particular circumstance will not be found in this report. However, the report does provide a guideline by which a credible answer to this question can be obtained through a modest amount of testing and analysis.

This report was prepared by Douglas W. Amlin of the Photographic Branch, Mission Avionics Division, Directorate of Avionics Engineering, Deputy for Engineering, Wright-Patterson AFB, Ohio. The author's conclusions are based on the references cited herein and numerous conversations with individuals familiar with this subject; namely: Messrs. T. Peterson and D. Fischer, Air Force Materials Laboratory; Major H. Rust, ASD/AERS; Mr. D. Mathews, 4950/FFAE; Mr. P. Miles, Raytheon Company; Mr. J. Kurdock, Perkin-Elmer Company; Messrs. J. Myers and E. McCrumm, Ford Aerospace and Communications Corporation; Messrs. R. Vantrease and G. Snellen, ASD/ENAMC.

I - INTRODUCTION

A review of available test data and theoretical analyses leads to the formulation of a method for predicting the rain erosion resistance of infrared window materials. Mathematical modeling of rain drop impact phenomena is used to provide a prediction of maximum tensile stress in any material as a function of impact angle, drop size and velocity. Incubation time is then estimated as a function of rain rate by correlation of test data with stress predictions. Computations are completed and results presented for the Pave Tack Zinc Sulfide window. More experimental data is necessary before predictions can be made for Gallium Arsenide and Zinc Selenide windows.

II - BACKGROUND

The use of airborne forward looking infrared imaging (FLIR) systems is limited by the availability of an infrared transmitting window to act as a barrier between the FLIR and the dynamic environment of the aircraft. Infrared window materials generally have undesirable physical properties, one of which is resistance to rain erosion. Only a few materials are currently being considered for FLIR's operating in the 8 to 12 micron wavelength region. Zinc Sulfide is generally accepted as the best of these materials for FLIR window application, although its optical transmission is not ideal. Pave Tack, a laser target designator FLIR system for F-4/F-111, is scheduled for production through 1982 utilizing a large Zinc Sulfide window. The theory and data which has been compiled to date on the rain erosion resistance of Zinc Sulfide (ZnS), Zinc Selenide (ZnSe) and Gallium Arsenide (GaAs) are summarized here with particular emphasis on application to the Pave Tack system.

The following information has been compiled during the last five years by AFML, AFAL, ASD and several contractors.

A. <u>Laboratory Testing</u> - Laboratory rain erosion tests have been conducted by AFML using a rotating arm apparatus. Standard conditions for the tests were:

1. One inch/hour rainfall
2. 1.8 mm drop diameter

3. 470 MPH velocity (also 575 MPH)

4. 78° impact angle (12° from perpendicular)

(also 90° impact angle)

The three primary candidates for an 8 to 12 micron FLIR window (Zinc Sulfide, ZnS; Zinc Selenide, ZnSe; and Gallium Arsenide, GaAs) were subjected to various durations of rainfall. The results of uncoated samples show that ZnS is significantly superior to GaAs, which is slightly superior to ZnSe.

Anti-reflection (AR) coated samples of each of these materials were subjected to the same rain erosion test. Results have ranged from immediate loss of coating to adherence of the coating beyond the limits of the substrate. Both ZnS and ZnSe initially developed internal fractures with only a minor disruption of the surface. Conversely, GaAs develops surface damage which is nucleated at pre-existing surface scratches. Although GaAs is relatively hard, erosion damage progresses rapidly due to its large gain size. Fractures occur by cleavage along preferred crystallographic planes producing long straight cracks on the surface.

A mathematical model of raindrop impact phenomena has been formulated by Bell Aerospace and used to generate computer predictions of transient stresses induced in selected window materials for single drop impacts. Stresses were calculated for drop diameters of 0.7, 2.0 and 2.5 mm and impact velocities of 730 and 1120 ft/sec.

These conditions have been duplicated in experiments and the results indicate that the analytical model provides a reasonable representation of the drop impact process.

Recent testing (November 1977) by Bell Aerospace Textron under contract to AFML has investigated the effect of impact angle of single raindrops on homogeneous materials. ZnSe specimens were tilted at angles of 60°, 45° and 30° to 2 mm raindrops impinging at 500 MPH. A small amount of damage occurred at 45°, but no damage occurred at 30°. Tests at 60° produced obvious damage and previous tests at 90° produced a large amount of damage.

B. Flight Testing - A limited amount of flight time has been accumulated on various infrared windows made of ZnS, ZnSe and GaAs.

Texas Instruments (TI) has flown samples of uncoated and coated germanium (Ge) and GaAs side-by-side for over 800 hours flight time. Tests were aboard a Lear jet which encountered a variety of atmospheric conditions during the testing period. The results indicate that the GaAs is superior to Ge in long term durability. The real significance of this test is based on the fact that forward looking Ge windows have been used successfully on B-52s since 1969.

No instances of ZnS or ZnSe forward looking windows being flown through rain have been recorded prior to November 1977. It is suspected, however, that ZnS windows were inadvertently flown through

rain during flight testing of the Pave Tack pod. In July 1977 Window 9C was determined to have damage to its AR coating similar to coating damage of samples run in the laboratory rain erosion test by AFML. It was later determined that no rain erosion damage occurred in the ZnS substrate of Window 9C.

During November 1977 limited flight testing of uncoated 4 inches x 6 inches samples of ZnS and GaAs in rain was completed. The samples were mounted atop a T-39 aircraft at 45° from the line-of-flight. Flights were conducted at 460 MPH through one to two inches/hour of water sprayed from a KC-135 tanker and at 300 MPH through natural rain. Flight time was 30 minutes and 80 minutes, respectively. No damage to the samples occurred. The flow field surrounding the samples for this configuration is not precisely known. It is known that drop diameter for water sprayed from the tanker is small.

C. Coating Improvements - The rain erosion resistance of the window substrate is of little importance in a FLIR application if its anti-reflection coating is easily eroded away. Early IR windows of germanium had coatings which survived up to the limits of the Ge; however, initial laboratory testing of AR coated ZnS and ZnSe indicated this was not the case for these materials.

Concurrent to the fabrication and coating of the first Pave Tack windows, efforts were underway to improve the durability of AR coatings for both ZnS and GaAs. Results of an AFML contract

with Honeywell and independent research by Perkin-Elmer and Optical Coating Labs, Inc. indicate that AR coatings for ZnS are now available which will withstand exposure to rain up to the normal limits of the substrate material. Continuing work at Perkin-Elmer under AFML contract should result in the application of an erosion resistant coating to a Pave Tack window which will then be available for flight test.

D. Window Handling Durability - Four Pave Tack ZnS windows have been refurbished to date due to surface damage incurred during flight testing. Some of these windows are suspected to have been exposed to rain, but none have shown substrate damage characteristic of raindrop impact. Damage apparently resulted from improper handling and/or solid particle abrasion. There is little reason to hope that this type of damage can be reduced by improvements of the window substrate or coating. It is likely that similar damage would occur if the window material was ZnSe or GaAs, even though ZnSe is softer and GaAs harder. None of these materials will tolerate being gouged by a screwdriver or being impacted by hard particles (insects, dust, ice). All will withstand normal handling and cleaning procedures.

III - ANALYSIS OF VARIABLES

A better understanding of the variables affecting rain erosion can be formulated from a thorough examination of the data outlined thus far in this report.

A. Effect of Impact Angle - It has become generally accepted that ZnS can withstand a one inch/hour rainfall, 1.8 mm drop size, 470 MPH velocity, at 78° impact angle for approximately 20 minutes before significant* sub-surface cracking of the material is visible with the unaided eye. There are no present or planned operational systems which utilize a window which is at or near perpendicular to the airstream (except for the apex of domes). Therefore, it is important to extrapolate this data point to other impact angles. Some testing by AFML is now underway to validate any such extrapolation.

It seems reasonable that velocity multiplied by the sine of the impact angle Θ can be used to estimate the effective impact velocity of the material installed in an operational configuration. Thus, for a ZnS window installed at 45° from the line-of-flight, the effective impact velocity at 470 MPH is $V_{45^\circ} = 470 \sin 45^\circ = 332$ MPH.

Similarly, for a ZnS window installed at 45° from the line-of-flight, the required velocity for comparison to the 20 minute, one inch/hour rainfall test at 470 MPH can be estimated as

$$V_{78^\circ} = \frac{470 \sin 78^\circ}{\sin 45^\circ} = 650 \text{ MPH.}$$

* See Footnote, page 9.

B. Effect of Velocity - It has been determined by Bell Aerospace that peak stresses in the surface of a material subjected to rain are approximately proportional to the velocity of the impact squared. Bell Aerospace has also calculated peak tensile stress for a 2.0 mm drop impacting at 730 feet/second (500 MPH) for several IR window materials. This value is 28,400 PSI for ZnS. Thus, peak stress in ZnS for a different velocity can be estimated as

$$\sigma_{max} = \text{stress}_{max} = \left(\frac{V}{730}\right)^2 \; 28{,}400 \text{ PSI}.$$

C. Effect of Drop Size - In an analysis by Bell Aerospace similar to that for velocity, it has been determined that peak tensile stress at 730 feet/second (500 MPH) is proportional to drop diameter raised to the 0.55 power. This exponent appears to be a mild function of velocity since it changes to 0.7 at 1120 feet/second. Thus, peak stress due to impact for drop size "D" mm which is different from 2.0 mm can be estimated by multiplication of σ by the quantity $\left(\frac{D}{2.0}\right)^{.55}$, or $\left(\frac{D}{2.0}\right)^{.70}$ for velocities closer to the speed of sound.

D. Effect of Rainfall Rate - A change in the rainfall rate to other than the standard one inch/hour can be interpreted as a change in the number of impacts per hour for any given velocity. Incubation time (time of exposure prior to physical damage) is logically inversely proportional to number of impacts. Thus, the incubation time for rain rates other than one inch/hour can be scaled accord-

ingly as $t_{inc,R} \propto \frac{1}{R} t_{inc,1}$ where $t_{inc,R}$ = incubation time at rain rate R, and $t_{inc,1}$ = incubation time at one inch/hour.

Footnote:

Some damage may be visible after only five minutes. "Significant" is used in a qualitative sense in that a window with this much damage would be easily recognized. A quantitative means of assessing damage is difficult to apply. Loss of transmission of radiation in the infrared is measurable but rather insensitive due to the scattering rather than the absorbing nature of the damage sites. A practical method of describing the amount of damage is to simply estimate the percentage of the surface area which is apparently affected (cracked, frosted, pitted, etc.). In this case, "significant" implies approximately 25 percent of the sample area appears obscured by cracks.

IV - CONCLUSIONS

Application of this data to systems such as Pave Tack is possible after combination of the variables into usable expressions.

A. Combination of Variables - The effects of impact angle, velocity and drop size can be combined into one equation for the prediction of maximum tensile stress due to rain impact in an operational system. The maximum tensile stress along with rain rate can, in turn, be used to estimate the life of the window under those conditions. Using the symbols

Θ = impact angle

V = velocity of aircraft (MPH)

D = diameter of raindrops (mm)

σ = tensile stress due to impact

σ_{mat} = tensile stress calculated for standard conditions for the material in question (ZnS, ZnSe or GaAs)

The equation becomes

$$\sigma = \sin^2 \Theta \left(\frac{V}{500}\right)^2 \left(\frac{D}{2.0}\right)^{.55} \sigma_{mat} \qquad (1)$$

where

σ_{ZnS} = 28,400 PSI

σ_{ZnSe} = 31,100 PSI

σ_{GaAs} = 29,000 PSI

Once a value of σ is calculated, it can be compared to values of σ for known situations. For instance, the standard

conditions for multiple drop impact tests at AFML (1.8 mm drop size, 470 MPH, one inch/hour, 78° impact angle) produce significant visible damage to ZnS after 20 minutes. The value of σ for this situation is

$$\sigma = \sin^2 78^\circ \left(\frac{470}{500}\right)^2 \quad \left(\frac{1.8}{2.0}\right)^{.55} \quad 28,400$$

or

$$\sigma = 22,840 \text{ PSI}.$$

Thus, any combination of θ, V and D resulting in σ less than 22,840 PSI should result in little or no significant erosion in a ZnS window for 20 minutes of exposure to one inch/hour rainfall.

This method of analysis has obvious limitations. A value of σ higher or lower than 22,840 PSI is difficult to extrapolate to a longer or shorter incubation time because the failure mechanism of the material may be different for significantly higher or lower stress. For values of σ lower than 22,840 the incubation time could be much longer than the standard 20 minutes. No conclusive test data is available on this point; however, incubation time for a variety of IR materials has been estimated to be inversely proportional to velocity to the 4.0 - 7.0 power (G. Hoff and H. Rieger, 1972). The value of this exponent must be experimentally determined for each material of interest. It is certain, however, that incubation time decreases rapidly as velocity increases.

Extremely limited data on ZnS from AFML indicates that the state of erosion after 30 minutes at 470 MPH is comparable to the state after 5 minutes at 575 MPH. The exponent for incubation time can be calculated from these data points as approximately 8.0. Using this information along with the previously calculated σ for 470 MPH and the expression for σ as a function of velocity, an expression for incubation time can be formulated as

$$t_{inc} = \frac{20}{R} \left(\frac{22,840}{\sigma}\right)^4 \qquad (2)$$

where

t_{inc} = incubation time in minutes

σ = stress in PSI calculated for the appropriate conditions

R = rain rate in inches/hour

Furthermore, an expression for estimating the fraction of the life of a window which has expired as a result of exposure to a variety of conditions can be formulated in terms of σ for each condition as

$$F_{life} = \frac{1}{20} \sum_{n=1}^{N} \left[R\left(\frac{22,830}{\sigma}\right)^{-4}\right]_n t_n \qquad (3)$$

where

F_{life} = fraction of life used

N = number of different combinations of R and σ encountered

t_n = time of exposure in minutes at condition "n"

B. The Pave Tack Problem - It is now possible to better assess the ability of an IR system to withstand rain damage in an airborne environment if sufficient data on the window material exists. Since the Pave Tack System is of current interest, the Pave Tack ZnS window has been chosen here as an example.

Application of equations (1) and (2) to the Pave Tack configuration (ZnS window, 45° impact angle) results in Figures 1 and 2. In Figure 1 maximum tensile stress is plotted against velocity for several sizes of raindrops. Figure 2 illustrates the variation of incubation time as a function of maximum tensile stress. Consider, for example, a velocity of 700 MPH and 1.8 mm drop size. Figure 1 shows a maximum tensile strength of 26,000 PSI results from the droplet impact. For this stress at a one inch/hour rain rate, Figure 2 shows that incubation time is approximately twelve (12) minutes.

Several additional points must be kept in mind when trying to make accurate predictions for Pave Tack. First of all, the impact angle for Pave Tack is always less than 45°. This is due to the nose of the pod (forebody) causing the free stream flow field to deviate drastically in the vicinity of the window. Also, the highest angle of impact (whatever it may be) is only realized when the turret is in its forward looking position; i.e., not slewed to any other point in the lower hemisphere. A second point to consider

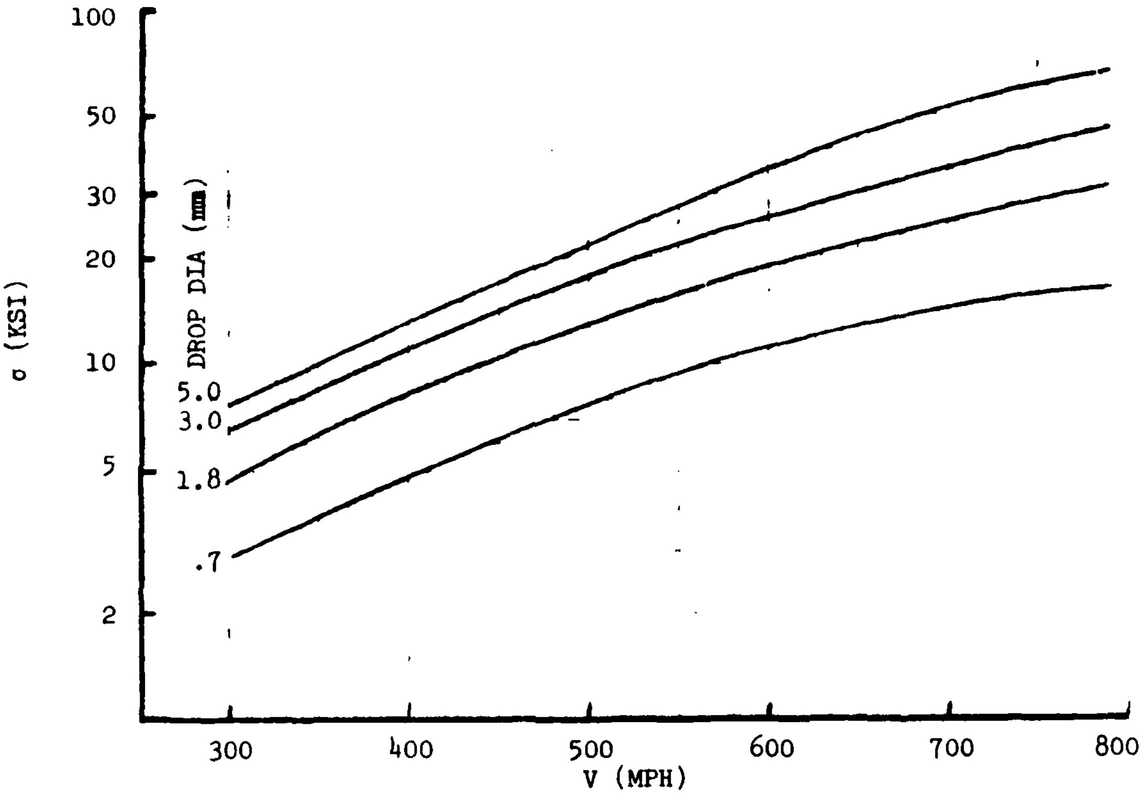

FIGURE 1

MAXIMUM TENSILE STRESS VERSUS VELOCITY
FOR IMPACT BY RAINDROPS OF VARIOUS
DIAMETERS (PAVE TACK SYSTEM)

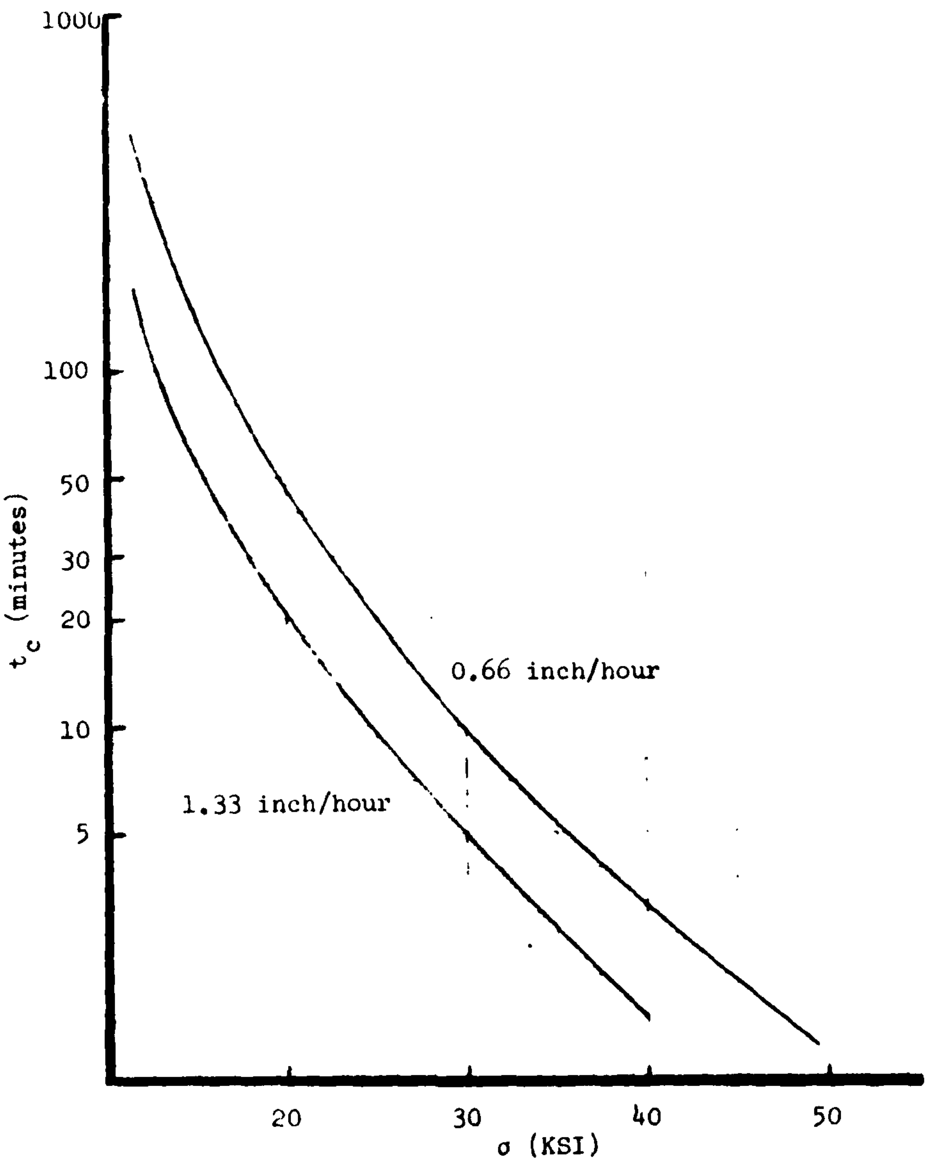

FIGURE 2

INCUBATION TIME VERSUS MAXIMUM
TENSILE STRESS FOR A ZNS WINDOW

is that any natural rainfall usually contains an undefined distribution of drop sizes falling at an undefined instantaneous rate. Equation (3) can be used to account for these variables to the extent that they are known or can be estimated. Lastly, the extent of operation of Pave Tack in rain must be considered. Heavy rain is usually encountered at fairly low altitudes where airspeeds are routinely lower in proportion to the severity of the rain. High speeds are usually for short durations. The amount of time Pave Tack is operated in rain is minimal due to factors other than rain erosion; i.e., poor transmission of IR energy through high humidity.

C. Other Applications - Application of this estimation technique to other systems can be made provided impact angle can be determined and data is available on the IR material to be used. The data presented thus far on ZnS needs to be substantiated by more testing and further refinement of analytical techniques. Data available on GaAs and ZnSe is very limited but is gradually being compiled under continuing work by AFML.

An interesting calculation can be made based on some experimental work with ZnSe. It has been shown that for a single 2.0 mm drop, 90° impact at 400 feet/second there is no evidence (by microscopic examination) of damage to ZnSe. In fact, the threshold impact velocity for ZnSe may be closer to 500 feet/second. Using the calculated (Bell Aerospace) value of 31,100 PSI for the maximum

tensile stress at 500 MPH for ZnSe, the maximum tensile stress at 400 feet/second is 9211 PSI. This stress level is approximately 23% higher than the flexural strength of ZnSe (7500 PSI). Notably, the maximum tensile stress in ZnS for the 470 MPH, 1.8 mm, 78° impact angle test is 22,840 PSI, which is 27% greater than the flexural strength of ZnS (18,000 PSI). Thus, a further analogy between the two materials would imply that t_{inc} is on the order of 20 minutes for ZnSe for $\sigma = 9211$ and $R = 1$ inch/hour. A proposed system limited to this σ, R and t_{inc}, with impact angle of 35°, would then be expected to have a maximum allowable velocity in 0.7 mm diameter rain (small drop rain field) of 633 MPH.

It should be emphasized that a firm basis for this last calculation does not yet exist. The large difference in grain size between ZnS, ZnSe and GaAs makes any analogy of their properties speculative. It is possible though that even ZnSe could be used successfully in some applications.

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